Agroforestry Systems **53**: 195–203, 2001.

Research methods for multistrata agroforestry systems with coffee and cacao: recommendations from two decades of research at CATIE

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Key words: experimental designs, on-farm research, sampling criteria, shade trees

Abstract

This paper reviews the research themes and methodologies used by CATIE in agroforestry research with shade trees over coffee (*Coffea arabica*) and cacao (Theobroma cacao) during the past 20 years. Initially research focused on characterization and production studies (of crop and timber including border areas) of traditional systems using temporary and permanent sample plots on private farms. The assessment area of traditional shade-coffee (or cacao) systems should be the whole plot, including the border areas, and not some subjectively selected central area which supposedly represents unit area productivity. Uncontrolled crop, tree, and management heterogeneity limited extrapolation of early on-farm research results to other farmers' fields. Replicated case studies of best bet technologies (traditional or experimental) on different farms are often preferable to the use of formal experimental designs. On-station research included the use of systematic spacing designs to test extreme shade tree density treatments of coffee. Most nutrient cycling studies were also carried out on-station, using service and timber shade species over coffee and cacao to evaluate the ability of these agroforestry systems to maintain nutrient reserves and diversify production. Plot size (even 36×36 m) was limiting for long term research because of inter-plot interference, both below- and above ground, when using fast growing, tall timber trees as shade. These experiences suggest a minimum plot size of 2,500 m^2. Individual tree designs and tree-crop interface studies (e.g. regression analysis of data taken along transects) are promising experimental/sampling approaches that need further development. The principal research thrusts proposed for the next five years are bio-physical process research on coffee responses to shade and competition with trees (growth, carbon allocation, phenology, disease-pest tolerance, yields and coffee quality effects) and socioeconomic analyses of both traditional and new or improved shade – coffee combinations *vs.* monocultures.

Introduction

Agroforestry research with coffee (*Coffea arabica*) and cacao (*Theobroma cacao*) has occupied a prominent place in CATIE's (Tropical Agricultural Research and Higher Education Centre, Turrialba, Costa Rica) agenda since 1979. Research foci and methodologies have been strongly influenced by both external and local factors. Key external factors included paradigms in the scientific and development community, such as: a) the rediscovery of the advantages of integrated production of food and tree products on the same unit of land; b) the use of forest ecosystems as templates for sustainable agricultural production systems (Ewel, 1986); and c) socio-cultural acceptability as a pre-requisite for agroforestry research and development (Bene et al., 1977). Influential local

factors included: a) most of Central America is in humid tropical areas below 1,300 m altitude (i.e. zones where coffee and cacao are commercially important); b) many traditional coffee and cacao agroforestry systems (AFS) include legume 'service' trees and/or valuable fast-growing timber trees as part of the shade canopy; and c) agroforestry research was mostly lead by foresters (hence the strong emphasis on timber trees). In this paper, we review the themes and methodologies used in CATIE's agroforestry research programme with coffee and cocoa over the past 20 years and suggest future directions for agroforestry research with these crops.

Evolution of research tropics

Research evolved in three major fields: a) improvement of traditional agroforestry systems with coffee and cacao; b) nutrient cycling in shaded coffee and cocoa; and c) shade management in cacao plantations.

Improvement of traditional agroforestry systems with coffee and cacao

Early descriptive inventories of traditional agroforestry systems with coffee and cacao (Salas, 1979) lead to more quantitative studies of species richness, vertical structure and product diversification in small coffee plantations (Lagemann and Heuveldop, 1983 cited in Beer et al., 1998). Data analysis methods were borrowed from forestry: e.g., overstorey stand density measures, species' importance values and vertical profiles were based on inventory data from 1,000 m^2 plots as was common practice in the study of tropical forests. Coffee production (González, 1980 cited in Beer et al., 1998), the effects of shade on coffee quality (Muschler, 2001), soil erosion (Bermudez, 1980 cited in Beer et al., 1998) and biomass production of the shade tree *Erythrina poeppigiana* (Glover and Beer, 1986; Russo and Budowski, 1986) were determined in private coffee plantations. Descriptive data were complemented with management (Marmillod, 1987) and economic information (Platen, 1985), including financial sensitivity analyses to changes in tree and crop productivity, prices, labor costs and interest rates (Hernandez et al., 1997; Platen, 1992).

Farmers provided detailed information on crop management and yields but little was known about tree growth and management. Dynamic studies of crop production and particularly timber growth were conducted in several private farms using permanent sample plots. Special attention was given to the estimation of tree stocking density, tree growth (dendrochronology, volume and stand tables; Beer et al., 1998), and to the enumeration of perceived advantages and disadvantages resulting from including shade trees. Studies were concentrated on naturally regenerated stands of valuable timber species like *Cordia alliodora* and *Cedrela odorata*. Practical criteria to select both farmers and measurement plots in private farms had to be developed (Beer, 1991) and, once again, methods were borrowed from forestry, e.g., for permanent sample plots (Synnott, 1979). Population transition matrices, borrowed from population ecology, were used to estimate timber yield in naturally-regenerated uneven-aged stands of *C. alliodora* in coffee plantations (Somarriba, 1990 cited in Beer et al., 1999). Simulation was used to model the economic advantages and disadvantages of harvesting timber trees in coffee plantations (Somarriba, 1992 cited in Beer et al., 1999).

Optimal shade tree densities over coffee was determined (on-station) through regression analysis focusing on the quantification of competitive interactions between shade trees and crop plants (Beer, 1992 cited in Beer et al., 1998). The experimental tree densities (*C. alliodora* and *E. poeppigiana*), chosen from within the range of values typically found on local coffee plantations (100–300 trees ha^{-1}; Beer et al., 1998), were superimposed on each other and on the straight coffee rows by using a two way systematic parallel row design (Mead and Stern, 1980). Thus the full range of densities of both species could be studied on a relatively small area (100×60 m) to avoid the costs of managing large and hence more heterogeneous areas of coffee with only a few treatments in a more traditional design. For example, at 100 shade trees ha^{-1}, a 6×6 tree plot (only 16 central measurement trees) would require 0.36 ha and three replications of only this treatment would require > 1 ha. Coffee was planted one year before

the trees and its initial growth (particularly stem diameter) was used as a co-variable to correct for any confounded site factors.

Nutrient cycling in shaded coffee and cacao

An increasing interest in process research, and in particular the need to quantify the ability of agroforestry systems to maintain nutrient reserves, was emphasized at an early stage. Studies were initiated on private farms with traditional shade management (Glover and Beer, 1986). However, the need for controlled management, soil homogeneity and security ('clean' data and protection of expensive equipment) motivated a shift back to on-station research. Biomass and nutrient accumulation in stems, branches, leaves, litter, roots and soil was studied with compartment models at zero (soil only), five and ten years age (Fassbender et al., 1991; Fassbender, 1993). Further studies included litterfall, crop and timber production (Beer et al., 1998), water and nutrient balances (Imbach et al., 1989; Jimenez, 1986), organic matter decomposition (Vilas, 1990), fine root turnover (Muñoz and Beer, 2001), soil chemical changes (Fassbender, 1993), and financial performance (Platen, 1992).

Litterfall methods were borrowed from natural forest research. Soil organic matter concentrations and input-output ratios for nutrients were used as indicators of the systems' ability to maintain nutrient budgets and hence sustainability. Meshbag techniques and regression analyses were used to measure and model litter and root organic matter decomposition. Atmospheric N fixation by the service shade tree species *E. poeppigiana* (Lindblad and Russo, 1986 and Nygren, 1995, cited in Beer et al., 1998) was measured on nearby on-station sites with conditions similar to those in the main experiment.

Shade management in cacao plantations

Long-term (> 10 years) on-farm experiments were established to develop shade management alternatives for different cacao genotypes using either leguminous service shade tree species (*Gliricidia sepium*, *E. poeppigiana* or *Inga edulis*), timber tree species (*C. alliodora*, *Terminalia ivorensis* or *Tabebuia rosea*) or more complex systems with plantains (*Musa* AAB) and *C. alliodora*. Data were analyzed using split plot designs, even though the cacao crosses were intimately mixed (physically identifiable split-plots of only one interclonal cross did not exist) to permit pollination of these self-incompatible inter-clonal crosses. Hemispherical photography and other visual techniques were used to monitor shade management (i.e., pruning and thinning; Lujan, 1992 cited in Beer et al., 1998) and its effects on cacao phenology (Boulay et al., 2000) as well as dispersal of *Moniliophthora roreri* spores, a major cacao disease (Meléndez and Somarriba, 1999). Farmers' participation in research was sought, but persistently low cocoa prices until the mid 90's reduced their motivation, especially during the early years when cacao was still unproductive. Adoption and adaptation by indigenous farmers of technologies to establish *C. alliodora* in existing cacao plantations was recently studied using participatory research techniques (Matos et al., 2000). Financial analyses used standard techniques but risk analyses were based on novel econometric modeling of product prices (cacao, plantains and timber) and on simulation of the cumulative probabilities of farm incomes for each technology (Ramírez et al., 2001). In the search for optimal management, shade species were pruned and thinned differentially according to cacao needs, tree growth, foliage and canopy architecture, and their tolerance to frequent severe pollarding. Individual factors (such as shade level or pruning frequency) could not be studied separately in on-farm trials due to their impracticality and negative effects on cocoa yields. Thus systems rather than individual factors were compared.

Methodological limitations and recommendations

Improvement of traditional agroforestry systems with coffee and cacao

Several problems related to the use of formal experimental designs on private farms repeatedly occurred: i) plots were often too small to avoid interference between treatments; ii) blocks were not homogeneous and their designation arbitrary (occasionally unjustified); iii) studies were often

of relatively short duration (≤ one year), sometimes because conditions on the farm changed; iv) many uncontrolled factors (natural and human influences) affected the results; v) research methods which require homogeneity of fields were used in heterogeneous stands (e.g., existing crop and tree stands); and vi) information on the previous management, origin, and age of the crop and tree components was unreliable. With hindsight, the use of standard agricultural and forestry research designs, such as random complete blocks, developed for controlled conditions on experimental stations, was often not appropriate for the diverse, spatially and temporally variable commercial plantations studied. Replicated case studies (using different farms as blocks) should be emphasized to reduce the effect of such problems. The use of permanent sample plots in private farms also faced several problems (see following section).

Scale

Many agroforestry systems are managed as small units (≤ 1 ha), although some components are large (e.g., timber trees). When border areas are excluded from evaluation, a necessity when results are to be applied within large contiguous agricultural or forestry areas, the average productivity, particularly of the trees, will be underestimated whenever these plots are bordering less competitive systems or open areas (Figure 1; tree production is relatively lower in the 'net plot'). The trees in the border areas of a plot usually grow better because they experience less competition than the trees in the center. This trend would be inverted for plots that are inserted into a forest, a relatively common situation for traditional timber-cacao (and some coffee) stands in Central America. In this latter case, the center (the 'net plot') would overestimate and the edges would underestimate the average tree productivity. Consequently, the assessment area of traditional shade-coffee (cacao) systems should be the whole plot, including the border areas, and not some subjectively selected central area which supposedly represents unit area productivity. However, results from whole-plot assessments can only be extrapolated to plots of similar size and shape in similar environments. These underlying

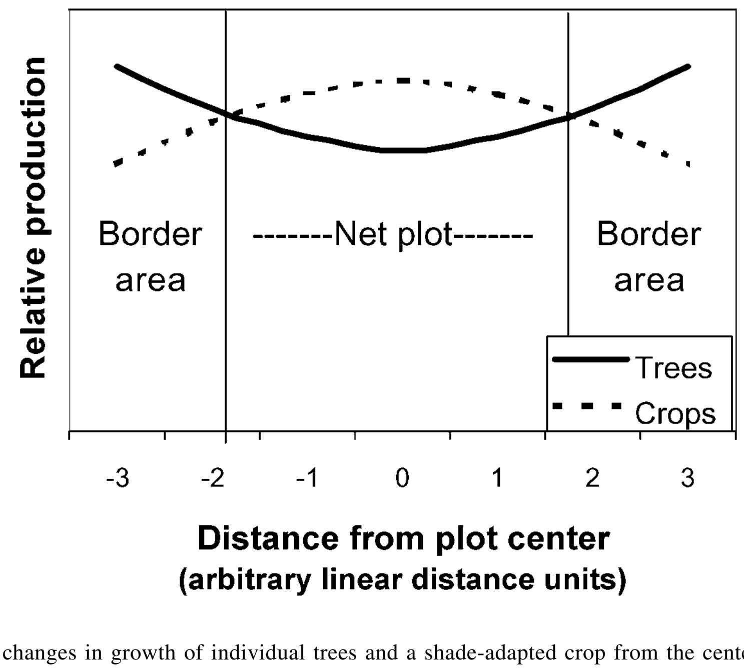

Figure 1. Hypothetical changes in growth of individual trees and a shade-adapted crop from the center of the net plot towards its edges (border areas): while the shade-adapted crop is relatively favored in the center of an agroforestry plot due to the shade of the trees, the diameter growth of individual trees is lowest in the center of the plot due to higher intraspecific competition among the trees.

restrictions for extrapolating data from plots, irrespective of whether they include border areas or not, indicate the need to assess the productivity of both areas. Such segregated data would then permit subsequent modeling of the productivity of plots of different dimensions and shapes.

Internal spatial variability

A homogeneous coffee field is rare. The coffee bushes usually have variable spacing, management (e.g., pruning) and ages, and may represent several varieties as a result of replanting. Tree stands are highly variable in spacing, ages, sizes and in species mixtures. Trees are usually derived from natural regeneration, which may not be permitted every year but rather at irregular intervals; tree harvest is irregular in time and space, affecting sample size and the precision of productivity estimates. Site conditions (soil, slope, etc.) are also highly variable; often experimental requirements for within-block and even within-plot homogeneity cannot be met. Furthermore, homogeneous agronomic management is rare in traditional systems, and the mere interest of the researcher in a particular plot may provoke intensified non-representative management. Control of pests and diseases is not uniform but rather localized according to the farmers' perceptions of severity, thus increasing within-plot variability.

When choosing permanent sample plots to study traditional shade-coffee or shade-cacao systems, it is important to decide what range of tree densities to include since this factor usually varies on the potential research sites from a few to an excessive number of trees per hectare. One approach is to subjectively choose only the apparently most successful examples as case studies to show the productive potential of the system under actual management. Such 'best examples' approaches have been used in studies of traditional knowledge (Biggelaar and Gold, 1995; Sinclair and Walker, 1999). It makes little sense to choose low tree density plantations unless enough is known about the system to suggest that these will have the greatest future potential, e.g., because the timber tree involved produces highly priced wood, or there is excessive competition at higher densities.

Nutrient cycling in coffee and cacao

Despite the use of plots that were considered large for agroforestry research in the 1980s, the following limitations were encountered in the on-station (0.065 ha plots) and on-farm (plots of up to 0.25 ha) nutrient cycling studies: i) tree roots had invaded neighbouring plots within 10 years (and probably earlier); ii) most litterfall occurred during gusty afternoon rains during which horizontal leaf transport from tall timber trees (e.g., *C. alliodora* at age 10 years) of up to 100 m was observed; iii) errors associated with the measurement of organic material and nutrient inputs via branch fall were high due to limited plot size; iv) with 6 × 6 m tree spacing, strong intra-tree competitive effects were also evident within 10 years (some border trees had 30–50% greater stem diameter) but thinning was not possible in the on-station plots because of limited sample sizes (only 10 'internal' trees) and the risk of damaging underlying crop plants (especially cacao); v) deep adjacent drainage ditches on a flat alluvial soil (on-station plots), assumed to cause lateral soil nutrient movement, limited the area available for leaching studies; vi) tall (> 20 m) timber trees caused shade interference on neighboring plots; vii) inventory values taken on one date may not be representative (e.g., litter, if taken immediately before *vs.* after annual leaf fall from *C. alliodora*; phenological cycles may vary among years); viii) representativity of samples for repeated (time series) nutrient reserve calculations (e.g., a cylindrical stem bore sample over-represents pith wood and under-represents phloem; taking representative samples from horizontal wedges would involve destroying the tree); ix) nutrient analyses made at five year intervals may have been affected by differences in field and laboratory techniques in addition to the possible temporal non-comparability mentioned above under point 'vii'; x) the altitude of the main on-station site (600 m) is close to the upper limit of the natural distribution of *C. alliodora* in Costa Rica and is not representative of most commercial Costa Rican coffee (too low) and cacao (too high) plantations; xi) the deep alluvial soil of this on-station site was not representative of the small hillside farms where most coffee and cacao are grown and where on-farm studies were carried out; and xii) agronomic

management of the on-station site was more intense and 'homogeneous' than that of many 'typical' farms (especially in low-input or no-input cacao farms).

Shade management in cacao plantations

Each cacao shade management trial was replicated on two or three farms. Natural disasters like floods and earthquakes and changes in land tenure or farmers' interest resulted in losses of at least one experiment of each type. Agroforestry research with cacao and shade trees (timber and service) requires a minimum of 10 years of data for a reliable estimation of cocoa production; timber trees may require > 15 years to complete a rotation. Trials are necessarily large (1–2 ha each) and costly. For instance, widely spaced (e.g., 278 trees ha^{-1}), tall (30–35 m at harvest time) shade trees, monitored over > 10 years, require large plots (> 1,300 m^2). Block designs need to include > 3 replicates per treatment to achieve the necessary discriminant power to detect differences between treatments. A complete trial can be accomodated only in medium to large farms. Moreover, it is very difficult to secure sufficient research funding for such large scale and long duration experiments.

As a result of these limitations, it is recommendable to keep the number of treatments to a minimum and replications may have to be established in non-contiguous plots, either on the same or on different farms. Plot size should ideally exceed 2,500 m^2 in order to minimize interference from adjacent plots or other land-uses as well as to allow for thinning and natural tree mortality, yet retain > 8 measurement trees per plot. This would allow monitoring for > 10 years and the collection of financial data on the different management regimes which would be unrealistic in smaller plots (even with large plots, financial data collected from bio-physical experiments may often be overestimates).

Several agroforestry technologies should be tested at the same time to allow for major unpredictable changes that may affect farmers' motivations over the long time frame typical of agroforestry research with perennial crops like cacao. In Costa Rica and Panamá, for example, changes in cocoa prices reduced farmers' motivations to adopt management-intensive alternatives (e.g., leguminous shade species over cacao which require frequent, costly prunings). Low-intensity management alternatives, such as timber enrichment planting in existing cacao plantations, were preferred by farmers under these price conditions. Other capital and labor intensive alternatives (such as the cacao-plantain-timber systems) were attractive to farmers with flat lands, alluvial soils, and easy access to nearby markets for selling the plantains.

Recommendations for current and future research with perennial crops

Recommended research themes

Current research at CATIE addresses: i) shade design and management in contrasting agroecological and socioeconomic scenarios in Central America (Bonilla and Somarriba, 2000; Llanderal and Somarriba, 1999); ii) organic coffee production and nutrient recycling using different forms of compost, green manures and tree biomass (Cobo et al., 1999, Castellón et al., 2000); and 3) root competition in timber–coffee systems (Schaller et al., 2001). Current studies of root competition between coffee and *Eucalyptus deglupta*, a fast growing timber species, and *E. poeppigiana*, a traditional service tree, are challenging the claim that tree roots generally develop below crop roots and, hence, recycle ('pump') nutrients to the crop through above-ground litter fall (natural and pruning residues). *E. deglupta* fine roots in coffee plantations are mostly found at 0–10 cm depths, while *C. arabica* roots dominate lower depths (Morales and Beer, 1998; Schaller, pers comm. 2001). Methods to reduce tree root competition with the coffee by limiting the spatial distribution of tree roots via directed fertilizer placement and the use of grass 'biological root barriers' have been tested (Schaller et al., 2001). Temporal differences in fine root growth between shade trees and cacao have been found and may offer an additional means of reducing nutrient competition by applying fertilizers when the cacao is developing new fine roots (at the beginning of the rainy season) and avoiding periods when the fine roots of the trees are

developing (at the end of the rainy season) (Muñoz and Beer, 2001).

The two main research thrusts proposed for the next five years are biophysical process research on coffee responses to shade and competition with trees (growth, carbon allocation, phenology, disease-pest tolerance, yields and quality effects) and socio-economic analyses of both traditional and new improved shade coffee combinations vs. coffee monocultures. The biophysical research should include further studies of nutrient cycling and competition for water and nutrients, in particular contrasting traditional leguminous service trees with fast growing timber trees. Applied research on coffee yields and quality, timber species selection for particular ecological conditions, and the adaptation of plantation silviculture to widely spaced timber trees in perennial crop plantations will continue to be needed. Adoption, decision and artificial intelligence models, product diversification, and financial stability and risk are to be tested. More attention should also be given to quantify the quality of ecosystem attributes such as water, air and biodiversity on the biophysical side, and indicators of the quality of life on the socio-economic side. Studies are needed on methods of technology dissemination and validation of improved agroforestry designs for systems that have medium to long term production cycles. Evaluation of management strategies and policy analysis are also needed. Intercropping of coffee and cacao with short term crops and the use of shade to control weeds in newly established plantations are further topics deserving research attention.

Methodological recommendations

Standard multivariate techniques (principal component, cluster and discriminant analyses), Anova and contingency tables have been developed to identify and rank the most important factors affecting shade design and management in Central American coffee plantations. Farmers' decision making regarding shade and coffee management has been studied in 'thought experiments'; e.g., contrasting imaginary scenarios are formed from combinations of pre-selected key factors and farmers' responses to these theoretical situations are recorded. Key factors presently considered include farm size, perceptions of coffee price stability, fertilization × shade × yield interactions, shade species selection and pathogen response to agroforestry technologies. Artificial intelligence models may help to analyze farmers' knowledge about the design and management of shade canopies for coffee.

In order to reduce the time and money needed to analyze the compatibility between crops and trees of different ages and sizes in traditional experimental designs, transect studies with temporary plots may hold promise (Huxley et al., 1989; Muschler, 1998). Regression techniques are used to study, in commercial plantations, the effects of individual trees on individual coffee or cacao plants at different distances from the trees (Figure 2). The main advantages of this approach are that: a) it requires only repeated, punctual observations rather than long-term experiments (e.g., there is no establishment period and hence it is cheaper and faster); b) it is adaptable to farmers fields, which also reduces costs; and c) the data will reflect more closely farmers' realities. The main disadvantages are: a) it does not permit direct conclusions on specific mechanisms of interactions; b) assumptions of homogeneity of crop and site attributes need to be met for laying out the transects; and c) there must be reliable information on the management history of the plots. Following exploratory work on five tree species (Muschler, 1998), the potential of this approach needs to be evaluated more broadly.

Conclusions

On-farm studies of traditional agroforestry systems are limited by uncontrolled variability of crops (density, age, varieties, etc.), tree stands (density, spacing, management), site (soils, slopes) and management in the study plots (temporal or permanent). Experimental approaches using standard designs (e.g., randomized complete blocks), either on-farm or on-station, require large (often too large) plot sizes. For work with large trees, a minimum plot size of 2,500 m^2 may be required. Long-term research (> 10 year) with tall fast growing timber shade trees inevitably involves inter-plot interference due to extensive root development or shading. Systematic spacing

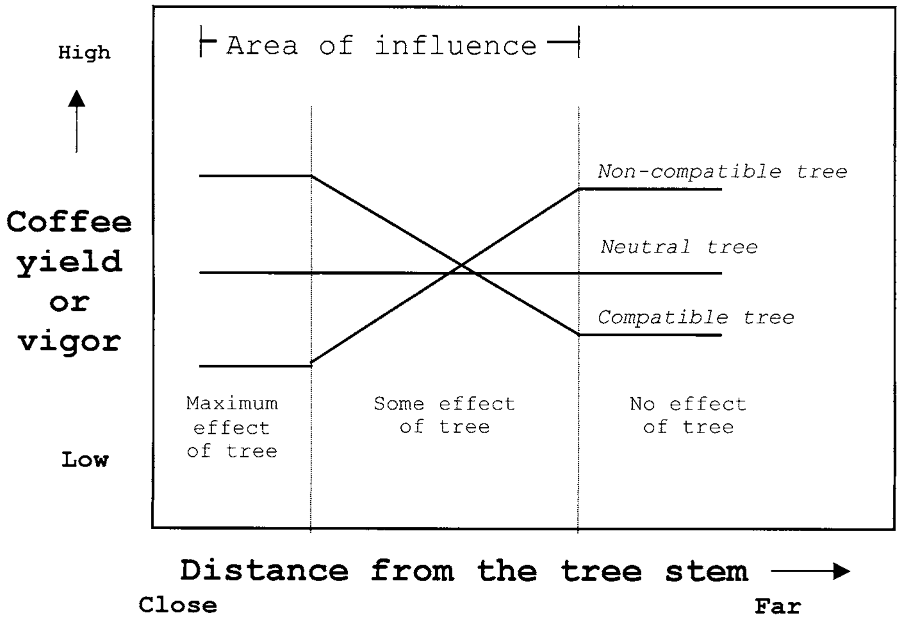

Figure 2. The performance of individual coffee plants at different distances from an individual tree can indicate whether this tree species is highly compatible, neutral or non-compatible with coffee (*source:* modified from Muschler, 1998).

designs for the study of shade tree densities avoid the need for huge trials, but are sensitive to site trends and to localized tree or crop mortality. Transect methods in farmer fields may provide an efficient alternative for the study of interactions between trees and associated crops, but their potential and limitations need to be explored in more detail.

So far, studies have emphasized biophysical interactions. In the future, more research attention should be given to dissemination, validation, and adoption studies of agroforestry technologies, to financial risk minimization through diversification of production systems, and to policy issues. Despite the claims that agroforestry is an environmentally sound approach to production, little specific research has been carried out on the macro-environmental 'service' impacts of agroforestry (e.g., biodiversity conservation, C-sequestration, water quality). More research must be devoted to these topics in shaded coffee and cacao plantations with more direct input and guidance from farmers as integral parts of truly participatory teams.

Acknowledgements

The authors wish to thank the colleagues and farmers who have been instrumental in running and evaluating the CATIE agroforestry research and validation plots over the past two decades. Special appreciation is due to the 'Gesellschaft für Technische Zusammenarbeit GmbH' (GTZ) and DANIDA for their financial support. We also thank two anonymous reviewers for their comments on the manuscript.

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